Calibration of atmospherically induced delay fluctuations due to water vapor

George Resch, Christopher Jacobs, Steve Keihm, Gabor Lanyi, Charles Naudet, Abraham Riley, Hans Rosenberger, Alan Tanner

Jet Propulsion Laboratory, California Institute of Technology

Contact author: George Resch, e-mail: George.M.Resch@jpl.nasa.gov

Abstract

We have completed a new generation of water vapor radiometers (WVR), the A- series, in order to support radio science experiments with the Cassini spacecraft. These new instruments sense 3 frequencies in the vicinity of the 22 GHz emission line of atmospheric water vapor within a 1 degree beamwidth from a clear aperture antenna that is co-pointed with the radio telescope down to 10 degree elevation. The radiometer electronics features almost an order of magnitude improvement in temperature stability compared with earlier WVR designs. For many radio science experiments, the error budget is likely to be dominated by path delay fluctuations due to variable atmospheric water vapor along the line-of-sight to the spacecraft. In order to demonstrate the performance of these new WVRs we are attempting to calibrate the delay fluctuations as seen by a radio interferometer operating over a 21 km baseline with a WVR near each antenna. The characteristics of these new WVRs will be described and the results of our preliminary analysis will be presented indicating an accuracy of 0.2 to 0.5 mm in tracking path delay fluctuations over time scales of 10 to 10,000 seconds.

1. Introduction

Two water vapor radiometers (WVRs) have been constructed in order to calibrate fluctuations in the line-of-sight path delay at radio wavelengths due to atmospheric water vapor. These WVRs will be used to calibrate fluctuations in the Doppler signals during the Gravitational Wave Experiment (GWE) with the Cassini spacecraft that is scheduled to start in Dec. 2001 and repeat in 2002 and 2003 during the spacecraft cruise to Saturn. The GWE has been described by Armstrong et. al. [1], and Tinto and Armstrong [2]. Studies of atmosphere delay fluctuations [3, 4] indicate that this phenomena is likely to dominate the error budget for the GWE on time scales of 100 to 10,000 sec.

The new WVR is shown in Figure 1 and has been described by Tanner [5]. This unit is located near Deep Space Station 13 (DSS 13) at NASAs Goldstone complex in the Mojave desert. In the background, slightly to the right of center in the photograph one can also see the microwave temperature profiler (MTP) and a WVR of earlier design (J-series).

The WVR measures equivalent blackbody brightness temperature at 22, 24, and 32 GHz. There is a spectral line originating from a rotational transition of the water vapor molecule centered at a frequency of the 22 GHz whose strength is proportional to the columnar content of water vapor along the line-of-sight which is related to the path delay.

The radiometer feed illuminates a main reflector of 1 m diameter in a offset configuration such that there is no blockage of the reflector that could cause scattering into the feed. The reflector can point in azimuth and elevation along the same line-of-sight as a nearby large communications antenna and has approximately a 1 degree beamwidth with very low sidelobe levels. Finally,

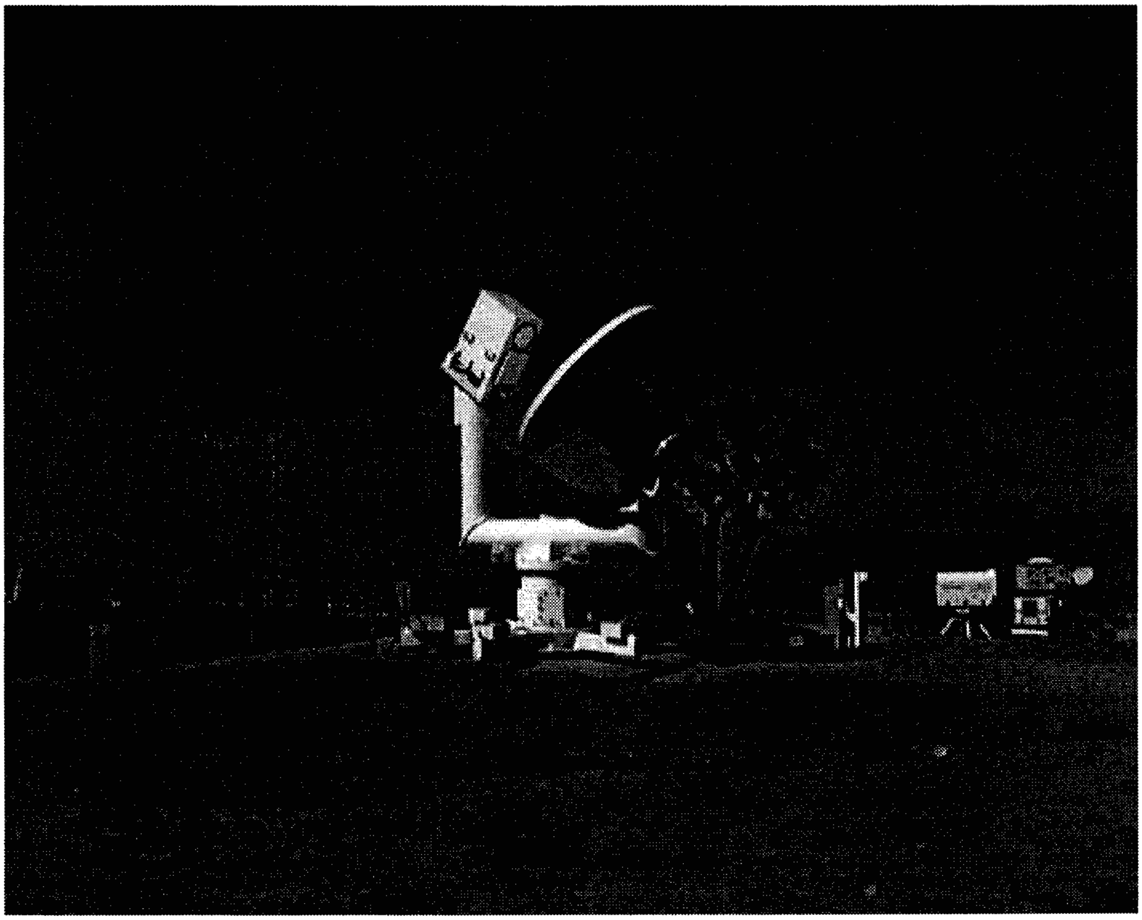

Figure 1. Photo of the new WVR taken at Goldstone near DSS 13. The MTP and a J-series WVR are shown in the background to the right.

the gain stability of the radiometer had to correspond to roughly 10 mK variation of brightness temperature for time scales as long as 10,000 sec.

2. Performance Demonstration

In order to demonstrate the performance of this new media calibration subsystem we examined its capability to calibrate another measurement technique that we knew to be sensitive to line-of-sight path delay fluctuations. The experiments were approximately modeled after the ones described in references [6, 7] using WVRs of an earlier design. The basic concept of the experiment is illustrated schematically in Figure 2.

Each new WVR was located within 50 m of the base of a 34 m antenna, located at the Goldstone Deep Space Communications Complex in the Mojave desert. In our experiments, the stations DSS 13 and DSS 15 were used and are separated by approximately 21 km. a used for additional snr in the following analysis. The WVRs were monitored in real-time but all data reduction was done in post-data acquisition. Each WVR measured the brightness temperature along its line-of-sight

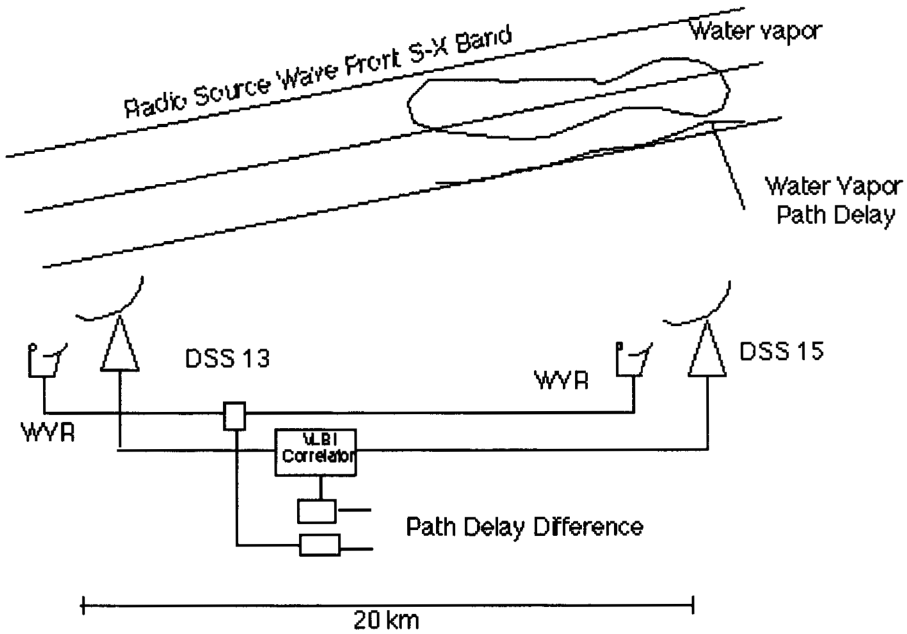

Figure 2. Schematic representation of the WVR/CEI comparison experiments

at sub-second intervals and produced a time tagged series of data that included the azimuth, elevation. The brightness temperature data were integrated for 6 sec. These time series were then used with two retrieval algorithms [8, 9] to estimate the line-of-sight delay. The data from each WVR were then differenced to provide a estimate of the differential phase delay between the two stations that could then be compared with the Connected Element Interferometer (CEI) residual phase delay. Finally, we calculate the Allan Standard Deviation [10] of the interferometer phase residuals is before and after correction by the WVR data in order to estimate the ability of the WVRs to calibrate atmospheric fluctuations as a function of time. This quantity is directly related to the requirements set by the Cassini GWE.

Typically the experiments were scheduled during night time hours using a two antenna CEI configuration. Only very strong sources (S > 1 Jy) whose positions were very well known (accuracy of better than 0.2 mas) were used. The objective in these experiments was to directly probe the quality of phase delay calibration on time scales of 10 to 10,000 sec under conditions similar to what is expected during the Cassini GWE. Each scan was scheduled for 1560 sec (i.e. the duration of a single pass on the Mark IV tape recorder). Several passes produced less data due to a variety of instrumental problems or operator errors.

The correlation process on the CEI data uses a priori estimates of several parameters in order to produce residual path delay and delay rate. Our fringe fitting software [11] removes a term in the phase delay estimate which is linear in time. This results in a estimate of phase delay that is zero mean over the entire scan. A similar linear rate was removed from the differenced time series of path delay for the WVRs

Figure 3 and 4 illustrate the best tracking accuracy we observed. In Figure 3 we plot the residual delay of the interferometer from scan 11 (day 240, 1999) after accounting for all geometric effects together with the differenced WVR delays and removing a linear trend in the differenced

WVR data. The rms of the CEI data in this plot is 0.65 mm and the correlation between the two data types is obvious. In Figure 4, we use the differenced WVR data to calibrate the CEI data. The rms of the residual in this case is reduced to 0.21 mm of path delay. Figure 5 shows the distribution of residuals for each step of the data analysis in scan 11. In panel (a) the CEI residuals are plotted, in panel (b) the differenced WVR data, and in panel (c) the calibrated CEI data. The reduction in variance is clearly evident.

Figure 6 plots the Allan Standard deviation as a function of integration time for scan 11. The dotted line in the each panel is the requirement for media calibration during the Cassini GWE.

3. Discussion

We have described the results from a preliminary analysis of a single scan from a series of experiments to that are designed to determine the performance of a new generation of WVR. During each scan in these experiments we observed a different radio source and tracked over a range of azimuth and elevation angles. When the WVR data is used as a calibration, the CEI residuals are reduced by a factor of 2 to 3.

The distribution of the calibrated data, as illustrated in the bottom panel of Figures 5 represent the quadratic sum of CEI errors plus WVR errors. In order to assess the performance of the new

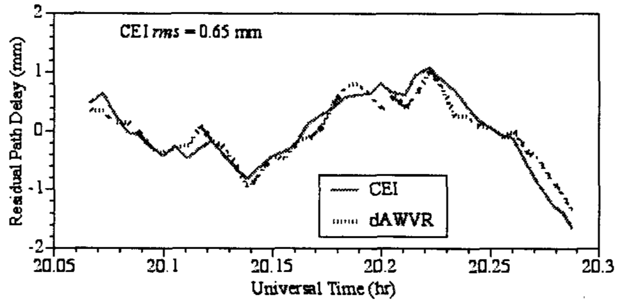

Figure 3. Residual delay of the connected element interferometer together with the residual delay of the differenced Water Vapor Radiometers for scan 11. Both data types mapped to zenith. The actual azimuth was 97 deg. and the elevation 29 deg.

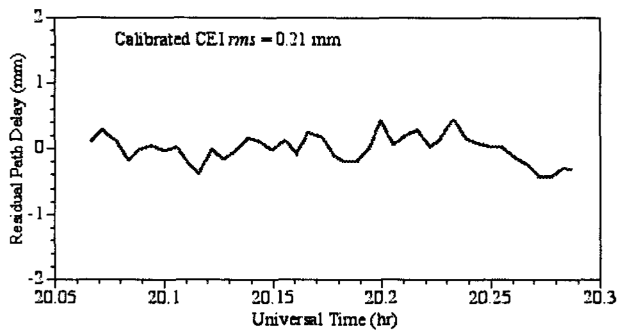

Figure 4. Residual delay of the connected element interferometer during scan 11 after correction by the differenced WVR data.

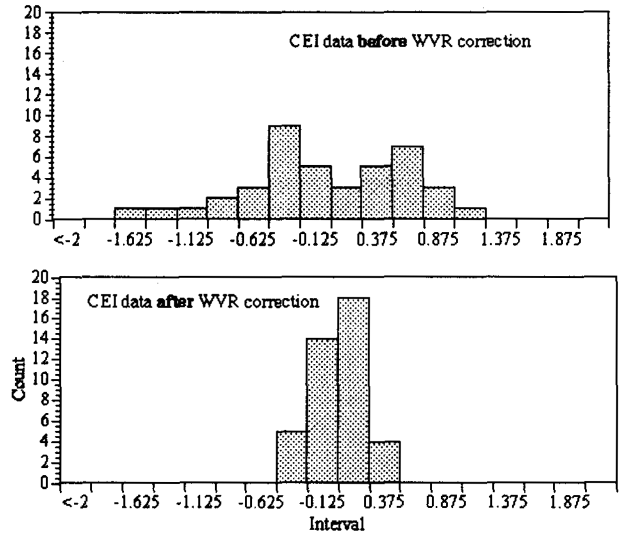

Figure 5. Histogram of the residuals from scan 11. Top panel shows the residual CEI path delay and the bottom panel shows the calibrated CEI data.

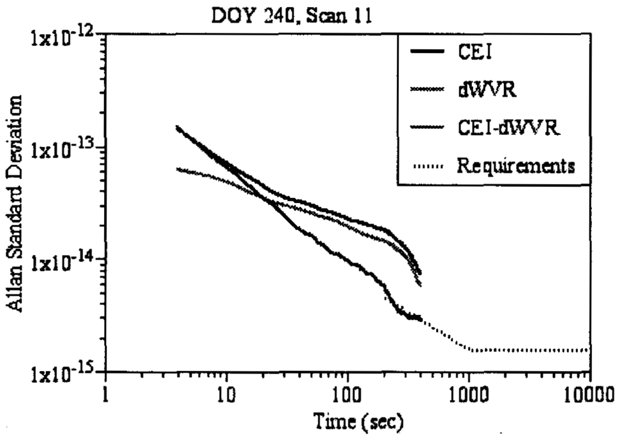

Figure 6. Allan standard deviation versus interval for 11 from DOY 240. Each plot shows the CEI residuals, the differenced WVR data, the calibrated CEI data (CEI-dWVR), and the requirements for the Cassini GWE.

WVR we must independently assess the error budget for each technique. For the WVRs, the components of the error budget are: a) Precision, b) Stability, c) Beam Size, d) Separation from main antenna, and e) Retrieval accuracy[12, 13].

For the CEI data the components of the error budget are are most important in these tests are; a) Electronics stability, b) Instrumental delay mis-modeling (including antenna deformation and subreflector motion), and c) Baseline accuracy. All of components must be reduced or estimated in order to infer the intrinsic accuracy of the WVRs. Our preliminary results strongly suggest that this error budget must be critically re-evaluated and this process is underway. Data analysis and additional experiments aiming to explore longer time scales are underway.

4. Acknowledgements

We are very grateful to Lyle Skjerve, Leroy Tanida, J. Eric Clark, Charles Snedeker, the staff at DSS 13, and the Operations crews at the Goldstone Signal Processing Center for the invaluable assistance provided during these experiments.

The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration

References

[1] Armstrong, J.W, B. Bertotti, F.B. Estabrook, L. Iess, and H.D. Wahlquist, "The Galileo/Mars Observer/Ulysses Coincidence Experiment", *Proc. of the Second Edoardo Amaldi Conf. on Gravitational Waves,* Ed., E. Coccia, G. Pizzella, and G. Veneziano; Edoardo Amaldi Foundation Series, Vol. 4, World Scientific, 1998.

[2] Tinto, M., and J.W. Armstrong "Spacecraft Doppler tracking as a narrow-band detector of Gravitational Radiation", *Phys. Rev. D,* **58**, 042002, 1998

[3] Armstrong, J.W., and R.A. Sramek, "Observations of tropospheric phase scintillations at 5 GHz on vertical paths," *Radio Science,* **17**, pp. 1579 - 1586, Nov. 1982

[4] Keihm, S.J. "Water Vapor Radiometer Measurements of the Tropospheric Delay Fluctuations at Goldstone Over a Full Year," *TDA Prog. Report* 42-122, pp. 1-11, 1995

[5] Tanner, A.B., "Development of a high-stability water vapor radiometer," *Radio Sci.,* **33**, pp. 449-462, Mar. 1998

[6] Resch, G.M., D.E. Hogg, and P.J. Napier, "Radiometric correction of atmospheric path length fluctuations in interferometric experiments," *Radio Sci.*, **19**, pp. 411-422, Jan. 1984

[7] Teitelbaum, L.P, R.P. Linfield, G.M. Resch, S.J. Keihm, and M.J. Mahoney, "A Demonstration of Precise Calibration of Tropospheric Delay Fluctuations With Water Vapor Radiometers," *TDA Prog. Report 42-126,* pp. 1-8, 1996

[8] Resch, G.M., "Inversion Algorithms for Water Vapor Radiometers Operating at 20.7 and 31.4 GHz," TDA Prog. Report 42-76, pp. 12-26, Oct. 1983

[9] Keihm, S.J. and S. Marsh, "Advanced algorithm and system development for Cassini radio science tropospheric calibration," *TDA Prog. Report 42-127,* pp. 1-19, 1996

[10] Allan, D.W., "Statistics of Atomic Frequency Standards," *Proc. IEEE,* **54**, No. 2, pp. 221-230, Feb. 1966

[11] Lowe, S., "Theory of Post-Block II VLBI Observable Extraction," *JPL Publ. 92-7,* 15 July 1992

[12] Linfield, R.P., and J. Wilcox, "Radio metric errors due to mismatch and offset between a DSN antenna beam and the beam of a tropospheric calibration instrument," *TDA Prog. Report 42-114,* pp. 1-13, 1993

[13] Linfield, R.P., "Error Budget for WVR-based Tropospheric Calibration System," *JPL IOM 35.1-96-012,* 5 Jun 1996